Dual, use-based definition of "system"

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Abstract. The standard definition (ISO 15288, 2008) of the concept of a system is not complete and is the definition of a closed system. Such a definition is inadequate for systems engineering. A use-based definition is proposed which spans the open-closed systems continuum by introducing inside-outside perspectives. Two typical uses in the context of the definition of a system are requirements analysis ("black box") and architecting ("white box"). The synthesis described in the paper leads to an inside system definition and an outside system definition. The inside system consists of a set of inside elements; a set of inside interactions; and a set of inside-outside interactions. The outside system consists of the system of interest; a set of outside elements; and a set of inside-outside interactions. Because the inside and outside definitions of systems are asymmetrical, the outside definition cannot simply be replaced by an inside perspective applied from the super-system level. By introducing the outside definition, the subtle difference between environment and super-system is surfaced. It is proposed that ISO 15288 use an open system definition and that the notion of purpose be removed from the ISO 15288 definition of a system.

1 Introduction

Since everything, then, is cause and effect, dependent and supporting, mediate and immediate, and all is held together by a natural though imperceptible chain which binds together things most distant and most different, I hold it equally impossible to know the parts without knowing the whole and to know the whole without knowing the parts in detail. (Blaise Pascal, 1660)

Why do we need to concern ourselves with the definition of a system? After all, definitions of the concept of a system have been around at least since the 1950s (Hall & Fagen, 1956) and there are standard definitions available today (ISO 15288, 2008) (these definitions will be presented and discussed in section 3). While teaching an introductory system engineering course, the author realised that this standard definition of the concept of a system is not complete. On reflection the standard definition is of a closed system. Such a definition is inadequate for systems engineering and since these definitions are used to mould young systems engineers, it is important that they reflect the latest thinking. This prompted further investigation which resulted in this paper.

Many fields are concerned with systems and thus relevant to systems engineering, but there is no single body of literature. New developments that occur independently in sociology, ecology and philosophy may benefit system engineering. "Systems" range from technical systems to enterprises and “systems of systems” with the latter two having a large social component (INCOSE, 2014, p. 12). In some small way, this discussion contributes to an evolving theory of system engineering.

The challenge of defining a system lies in balancing a practical definition that is theoretically sound while dealing with the recursive nature of the concept of a system. Another challenge is the communication of many concepts that are inter-related. In order to re-consider the notion of a system it is necessary to start at some point but fortunately the concept of a system is not new.

This paper first reviews of the criteria for a rigorous definition from philosophy and performs a cross-disciplinary literature review of definitions of a system (Montuori, 2013). The methodology for the synthesis of a new dual use definition of system is based on: i) the application of the criteria for a rigorous definition, ii) the characteristics of a system, found in the literature and iii) the notion of systems thinking in Pascal's quote above.

2 Considerations for a definition

There are several types of definitions that could be considered when developing a definition (Gupta, 2014):

1. **Dictionary definitions**: A nominal definition that explains the meaning of a term. Dictionaries provide definitions with sufficient information to impart an understanding of the term.
2. **Stipulative definitions**: A meaning given to a defined term, that does not need to agree with prior uses (if any) of the term. For example, "Let V denote the voltage across the terminals".
3. **Descriptive definitions** give the meaning of a term in a way that covers existing usage.
4. **Explicative definitions**: An explication maintains some central uses of a term but is stipulative on others. The explication may be offered as an improvement of an existing, but possibly imperfect concept. It may be offered as a "good thing to mean" in a specific context for a particular purpose.
5. **Ostensive definitions** convey the meaning by pointing out examples. Suppose that in the context of a conversation one dog stands out amongst several dogs that are visible. One can then introduce the name 'Wilber' through the stipulation "Let Wilber be the dog that stands out".

The type of definition of "system" that is required is an explanatory definition - the central meaning is maintained, but some improvements will be proposed. Two criteria are required in terms of basic theory of definitions in philosophy: Use and conservativeness (Gupta, 2014) (Belnap, 1993). First, an explanatory definition should explain *all the meaning* of a term by explaining its use in every context - this is the use criterion (Belnap, 1993). Second, the definition *should not make assertions beyond all the meaning* of the term - this is the conservativeness criterion. There should be no statements that are not related to explaining the meaning of the word. The use and conservativeness criteria are necessary for an explanatory definition and together they are sufficient. These two criteria will assist in evaluating existing definitions and in the construction of a new definition. As will be shown in the next section, the use of "system" is already established in the context of system engineering and also more broadly.

3 A review of definitions of a system

According to Luhmann (2006) the development of systems theory is divided into three stages: (1) the theory of closed systems; (2) the theory of open systems; and (3) the theory of observing or self-referential systems. The transition from the theory of closed systems to the theory of open systems drew increased attention to the context or environment. More recent thinking suggests that systems are on a continuum between open and closed (Montuori, 2013). A system may be open to one aspect but closed to another. As an example, a car propelled by an internal combustion engine is open to energy in the form of fuel but closed to the high-pressure combustion.

There are many definitions of system, not all consistent, from different contexts. Only a selection of these definitions are listed in Table 1, illustrating each of Luhmann's three categories. The definition by Hall and Fagan is included as a departure point (D0S). The context in which the authors propose the system definition is very much physical systems as evidenced throughout their paper. Hall and Fagan also include a definition of the environment (D0E) that is relative to the system. It is worth noting that Hall and Fagan make the following disclaimer and observation:

"Definition of the mathematical or philosophical kind are precise and self-contained and settle completely and unambiguously the question of meaning of a given term. The definition given ... certainly does not meet these requirements; indeed, one would be hard-pressed to supply a definition that does."[1] This serves as a warning that defining the concept of a system is not an easy task.

Table 1 Selected list of definitions of "system"

#	Definition of system	Reference
D0S D0E	A system is a set of objects together with relationships between the objects and between their attributes. For a given system, the environment is the set of all objects a change in whose attributes affect the system and also those objects whose attributes are changed by the behaviour.	(Hall & Fagen, 1956)
D1	A combination of interacting elements organized to achieve one or more stated purposes.	(ISO 15288, 2008)[2]
D2	A system consists of three related sets: • a set of elements • a set of internal interactions between elements • a set of external interactions between one or more elements and the external world; i.e. interactions that can be observed from outside the system.	(Aslaksen, 2013)
D3	Something is a system if and only if it meets the following properties: **Composition**: a set of elements of some category (physical, social, biological, etc.) **Environment**: a set of elements of the same category, such that the composition and the environment are disjoint. **Production**: the elements in the composition produce things (e.g. goods or services) that are delivered to the elements in the environment. **Structure**: a set of influence bonds among the elements in the composition and between them and the elements in the environment.	(Dietz, 2006)
D4	system *is* difference—the difference between system and environment.	(Luhmann, 2006)

According to the ISO15288 definition, D1, only the system elements interact. If it was intended that "elements" include external elements as well as system elements, then there is no notion of a system boundary and this would not be a suitable definition of a system. The notion of environment is mentioned in the standard, but no definition is offered. Although systems practitioners may know that a system exists in an environment or context, there is no mention of an environment in D1. D1 is the definition of a closed system - it is internally focused. Since an element can be a system, D1 is a recursive definition - this is in the nature of a system. The issue of purpose in D1 will be discussed in the next section.

Aslaksen's definition D2 is an open definition of a system that includes the interactions with the

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[1] The definition of system has similar challenges to defining left and right (Bateson, 1979, p. 83).

[2] Recent revisions of ISO 15288 such as ISO/IEC/IEEE FDIS 15288:2014(E) have the same definition as 2008 revision.

external environment as part of the definition. The environment is strongly implied through the use of the words "external world". Aslaksen's definition does not require purpose.

Dietz defines an ontological definition (D3) in the context of enterprise systems (Dietz, 2006). This definition explicitly includes the environment (i.e. it is the definition of an open system). Dietz explains that he uses ontological in opposition to teleological (goal or purpose based). It is different to the other definitions in that it requires that elements in the composition produce things. This definition has a balanced internal and external focus.

In self-reflective inquiry, the observer cannot be separated from the observation. An example of self-reflective definitions of system is Luhmann's definition D4 in the context of social systems. Luhmann himself notes the peculiarity of his definition which includes "system". This definition includes an environment and thus defines an open system. System appears in the definition as a reference because the environment is always relative to the system of interest. The constituent parts of the system are not mentioned in the definition leaving the balance of focus outside. Since Luhmann's concern is social systems and since these are always changing, this definition moves from structural definitions of systems to difference.

None of the definitions has an explicit system boundary - the system boundary is implicitly determined from a set definition or in the case of D4 through the concept of difference. D1 is the only definition reviewed that requires purpose. In the next section, the question of whether purpose is a necessary part of the definition is considered.

4 The issue of purpose

There are two possible meanings of purpose. This first is a dictionary definition: Purpose is the reason for which something is done or for which something exists (Soanes & Stevenson, 2006). The second is a use in practice that can be traced back to the 1940's, where purpose is used to mean goal (Rosenblueth, et al., 1943). It is not clear which of these is intended in D1.

The issue of system purpose is considered under two categories: systems that do not contain people and systems that contain people.

In the **first category**, and of particular interest in systems engineering, are systems that do not contain people. A system that does not contain people cannot have its own purpose (using the dictionary definition of purpose), so in such a case the stated purpose in D1 must be that of the stakeholders. For example, the function of a truck is to transport goods, but the purpose of a truck owned by a florist is to deliver flowers to customers. In this case purpose is inherent to the stakeholders and not the system. Let us suppose that the florist uses the truck to transport workers, which was not a stated purpose at design time. Does the "system" cease to be a system according to D1? No. Suppose that what the system does is not in line with its stated purpose. There may still be interactions, but it does not meet requirements. Does the "system" cease to be a system according to D1? No.

In the **second category**, systems that contain people, the system has three levels of purpose (Ackoff, 1974):

- System purpose;
- Purpose of the parts of the system and
- Purpose of the system in its environment.

In the context of an enterprise, for example, the challenge is that in a socio-cultural age, as opposed to a mechanistic age, each of the purposes can be misaligned (Gharajedaghi, 2011). Which level of purpose is of concern in the definition D1?

Whose purpose is it? Is it the purpose of the developer, owner, the user? What is the relation between the purpose of the system and the people that form a part of the system? Furthermore, let us suppose that a system has a designed purpose, but the users do not accept the system for that purpose. Does the "system" cease to be a system according to D1? No. Thus the purpose of a system is determined by the interests of various stakeholders.

For a rigorous explanatory definition, purpose is not necessary in terms of the conservativeness criteria, since it is introducing facts that are not required to explain meaning. Furthermore, there are challenges regarding purpose in systems that include people because of human autonomy.

5 A dual definition of a system

In systems engineering, there are a number of different processes in realising a system (INCOSE, 2010). Two of these are highlighted in the context of the definition of a system: Requirements analysis and architecting. Requirements analysis treats the system as a "black box". Architecting is concerned with designing the system ("white box"). A definition of a system must satisfy both uses in the context of system engineering. How do we know these are all the uses? The position here is that other uses in the context of validation or verification can be related to the two uses already proposed, or are independent of the definition. To further answer this question a framework of perspectives is required.

Wilber identifies eight fundamental perspectives for understanding on three dimensions: {singular, plural}, {interior, exterior}, and {inside, outside} (Wilber, 2007). As Wilber explains, no perspective is privileged in terms of understanding. All are required. Two of these perspectives are relevant here: outside and inside. Other authors have also used these two perspectives with reference to artifacts (and technical systems are artifacts):

"An artifact can be thought of as a meeting point ... between an "inner" environment and an "outer" environment, the surroundings in which it operates." (Simon, 1996)

In the context of this paper, the outside perspective is the view of the system as a whole in its environment and the inside perspective is a view of the parts that make up the whole. The emerging properties of a system can be observed at the system boundary without observing the elements of the system. This is the outside perspective of importance for requirements analysis. Current definitions of systems are either an inside perspective or a mixture of inside and outside perspectives. There is currently no outside definition of a system in the context of system engineering.

Two system definitions are proposed: an outside and an inside definition. The two definitions correspond with use in systems engineering but can also be seen as two different perspectives. For example, when doing requirements analysis the system is treated as a whole, but part of the environment - the outside perspective. During architecture development, the parts of the system are considered - the inside perspective. The part-whole nature of a system is fundamentally intertwined and leads to the recursive definition of a system.

The building blocks of the proposed definition of a system are:

- Elements (either inside or outside) that may themselves be systems, i.e. the definition applies recursively;
- Interactions that occur based on the organisation of the elements;
- A set of inside elements. The inside elements are a part of the system. They are system elements. There must be at least two inside elements (unless the inside element is a system);
- A set of outside elements. The set of outside and the set of inside elements are disjoint, i.e. an element cannot be inside and outside simultaneously. For a closed system the set

of outside elements is empty;

- A set of inside interactions; and
- A set of inside-outside interactions, which for a closed system is empty.

The definitions provided implicitly define a system boundary through membership of the inside and outside sets.

Inside system definition (ISD) An inside system consists of:

- A set of inside elements;
- A set of inside interactions; and
- A set of inside-outside interactions.

Outside system definition (OSD) An outside system consists of:

- The system of interest;
- A set of outside elements; and
- A set of inside-outside interactions.

Only an open system can have an outside system definition. Since "system" is used in the OSD we have a recursive definition, which as Luhmann points out about his definition, is a paradox. The use of "system" in its definition provides a *reference* for the environment or the set of outside elements. The notion of an inside definition and outside definition allows part-whole consideration of a system. A system design is feasible if and only if its outside behaviour matches its inside behaviour. It is important to note that the outside of system is "environment" and not "super-system". Whereas the ISD requires a set of inside interactions, *the OSD does not require a corresponding set of outside interactions* and thus the ISD and OSD are asymmetrical definitions. Finally, the concept of an environment is useful for context analysis.

The definitions are represented graphically in Figure 1 around the concept of systems hierarchy. The "system" level is the reference from which "outside" and "inside" perspectives are defined.

Are the ISD and OSD definitions reasonably correct? Four levels of consideration are proposed:

1. Do the two definitions meet the criteria for a rigorous definition summarised in section 3?
2. Are the two definitions self-consistent?
3. How do they compare to the existing definitions in the literature listed in Table 1?
4. Are we biased by worldviews in constructing such definitions? Are there any limitations?

Firstly, for an explanatory definition of system, such a definition should explain all the meaning by explaining its use in every context. This has been achieved through the construction of outside and inside definitions corresponding to use in requirements analysis and architecting. There are no statements related to purpose as in D1 or products as in D3 that introduce new facts about the notion of a system. The basic definitions can be specialised in a specific context.

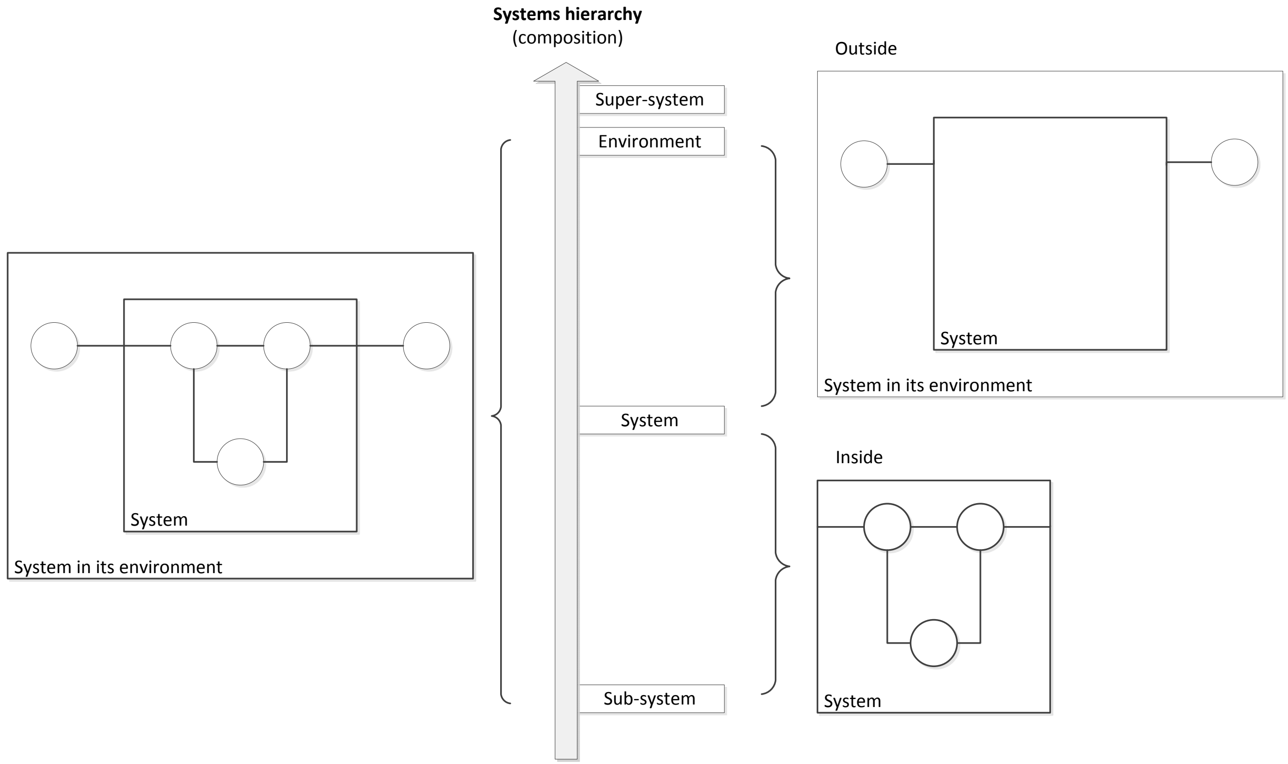

Figure 1 Illustration of the inside and outside definitions of system

Secondly the definitions of ISD and OSD are self-consistent, and together they result in an ontological definition similar to Dietz's definition (D3) of a system in its environment (illustrated on the left side of Figure 1):

- A set of inside elements;
- A set of outside elements;
- A set of inside interactions; and
- A set of inside-outside interactions.

Thirdly, comparing the proposed definitions to existing literature reveals that the ISD is of the same form as D2 and, as already discussed above, the overall form is similar to D3. Thus the OSD brings the correct aspects to the overall form.

Fourthly, biases, worldviews and limitations are considered. The proposed definition is constructed within the author's world views and must be evaluated over time. There are patterns of thought that arise from our education. For example, Descartes introduced some ideas for thinking about problems which have been instrumental in advancing some of the sciences and engineering:

If we are to understand a problem perfectly, we must free it from any superfluous conceptions, reduce it to the simplest terms, and by process of enumeration, split it up into the smallest possible parts. (quoted in (Montuori, 2013)).

This reductionist thinking must be carefully considered when the point is to apply systems thinking. In the case of the proposed definition, the reduction or abstraction is in the environment and not in the immediate system. In contrast, the environment of D1 is abstracted leaving a closed definition of a system.

The proposed definitions do not consider temporal change of systems over time. This can take one of three forms: system life-cycle, change to a technical system as it is maintained, or adaptation or evolution of systems to the environment. It is possible that system life-cycle could satisfy the conservativeness requirement. The notion of interaction must be considered carefully in the context of systems that contain people. Whereas in technical systems interactions are fixed and mechanistic, in systems containing people, meaning is fluid and interactions cause the system to change and adapt and even the environment can be influenced or changed. There are also some limitations of ISD and OSD in relation to D4, “system is difference” when the difference is not an “element”, for example, when the difference is subjective or inter-subjective (such as culture).

Thus, it is concluded that the proposed definitions are reasonable provided that care is taken when these are used in the context of systems containing people.

6 Conclusions

I shall proceed from the simple to the complex. But in war more than in any other subject we must begin by looking at the nature of the whole; for here more than elsewhere the part and the whole must always be thought of together. Carl von Clausewitz

The generally accepted nature of a system is changing across various disciplines as the context of use expands and understanding deepens. This poses a challenge for systems engineers, given that the context for the definition of "system" ranges from technical system to systems of systems. A use-based definition has been proposed which spans the open-closed systems continuum by introducing inside-outside perspectives. Because the inside and outside definitions of systems are asymmetrical, the outside definition cannot simply be replaced by an inside perspective applied from the super-system level. Furthermore, by introducing the outside definition, the subtle difference between environment and super-system is surfaced.

ISO 15288 does not include a definition of an environment, and it can be argued that it is not required in the standard. However, it is recommended that ISO 15288 move to an open system definition and that the notion of purpose be removed from the ISO 15288 definition of a system.

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8 Biography

Duarte Gonçalves is a registered professional engineer with a B. Eng in Electronics Engineering, a M. Eng in Computer Engineering and a PhD in Engineering Development and Management. He is currently employed by the CSIR as a Principal Systems Engineer. He has been involved in engineering surveillance systems for the South African National Defence Force (SANDF) and has consulted to the Karoo Array Telescope and led a renewable energy project as a systems engineer. As part of effort to develop systems engineering skills at the CSIR and nationally, he has developed a practice-based systems engineering programme which is being presented at Wits University. More recently he has been involved in Force Planning and Design for the SANDF. He currently leads a Whole-of-Society approach to strategy development at the CSIR with border security and rhino poaching as the first applications of the approach.

Duarte has a strong interest in trans-disciplinary problems that span engineering, social sciences and strategy. His is a serious amateur photographer that has exhibited his work on several occasions.